

Future of Heterodyne Receivers at Submillimeter Wavelengths

Goutam Chattopadhyay

Jet Propulsion Laboratory, California Institute of Technology,
M/S 168-314, 4800 Oak Grove Drive
Pasadena, California 91109, USA,
E-mail: Goutam.Chattopadhyay@jpl.nasa.gov

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Abstract

Heterodyne receivers at submillimeter wavelengths are at a crossroads today, uncertain of their future and the role they will play in the next generation NASA missions. Even though they offer very high spectral resolution, they are intrinsically handicapped by quantum noise. With the proposed cold telescopes for the future NASA missions such as the SAFIR, the direct detector instruments will no longer be background noise limited, and will outperform the heterodyne instruments in the sensitivity arena. In this review paper we examine these issues very carefully and describe the novel receivers being designed to make heterodyne instruments more competitive. It will be shown that heterodyne instruments will still have significant roles to play in the near future.

Introduction

It is widely acknowledged that the far-infrared and submillimeter wave regions of the electromagnetic spectrum (100 GHz to 10 THz) provide critical tracers for the study of a wide range of astrophysical phenomena [1]. This spectral range contains information on the origin of the planets, stars, galaxies, and clusters; the geometry and matter/energy content of the Universe, atmospheric constituents and dynamics of the planets and comets and tracers for global monitoring and the ultimate health of the Earth.

Spectroscopy in the submillimeter and far-infrared frequencies is a vital tool in studying many of the important astrophysical phenomena [2]. Spectroscopic studies can be carried out using coherent (heterodyne) detectors or incoherent (direct) detectors in conjunction with grating, Fabry-Perot, and Fourier Transform Spectrometers (FTS) [3]. For ground based observatories, heterodyne instruments at submillimeter wavelengths continue to be the instrument of choice for high resolution spectroscopic studies. Large interferometric arrays such as the ALMA [4] will not only provide high spectral resolution, it will also offer excellent sensitivity and high angular resolution. However, it remains to be seen what significant role heterodyne instruments are going to play for future submillimeter wave space-borne observatories.

The next generation space-based instruments in the far-infrared and submillimeter wavelengths, such as the NASA's proposed Single Aperture Far-Infrared (SAFIR) observatory [5], will have large (10m-class) cryogenically cooled telescopes. The cold telescope will enable removal of all sources of thermal emission from the atmosphere and the telescope, making the detectors for such instruments detector-noise limited. This will make direct detector imagers and spectrometers more attractive at submillimeter wavelengths for studying the fundamentals of star and galaxy formation, dust and gas chemistry, and cosmology and CMB astrophysics. On the other hand, heterodyne detectors will always be quantum noise-limited [6]. Therefore, the future of heterodyne

instruments for future space-borne missions at submillimeter wavelengths is somewhat uncertain.

Heterodyne Vs. Direct Detection

One of the critical questions for future space-borne radio observatories at submillimeter wavelengths is whether to use heterodyne or direct detector instruments for spectroscopic studies. In general, heterodyne detection offers several advantages over direct detection, offering higher spectral resolution ($\lambda/\Delta\lambda \approx 10^6$) in particular [7]. Since heterodyne detectors measure both amplitude and phase simultaneously, they are governed by the uncertainty principle, and hence are quantum-noise limited to an absolute noise-floor of 50 K/THz. On the other hand, direct detectors are not quantum noise-limited, and when they are not background-noise limited, can provide unprecedented sensitivity provided grating spectrometer approach is utilized [8].

For ground-based observatories, high instantaneous bandwidth is not a must for spectroscopic studies. The reason being, one can have multiple bands to cover the frequency range of interest, and the size and mass is not an issue either, as in the case of space-borne observatories. Direct detector spectroscopy – though will require larger optical paths to get the required resolution – are preferable for spectral resolution in the 10^4 or lower range. For direct detector instruments, even though grating spectrometers are most sensitive, most often for practical reasons FTS or Fabry-Perot spectrometers are used, resulting in a loss of sensitivity. That puts them at par with heterodyne detectors when the instruments are background-noise limited. As for grating spectrometers, the instrument size increases with the increase in spectral resolution. For example, achieving 10^6 resolution at 2 THz will require a 150 m long grating (linear size = $R\lambda$, where R = resolution and λ = free space wavelength), which is a prohibitive size for a space-borne instrument. Moreover, the backend spectrometer does not need cooling in heterodyne instruments, which is not the case with direct detector spectrometers, putting more load on cooling requirements for space missions. Additionally, heterodyne instruments in reality have simpler optical system, giving them an edge in the overall efficiency [8].

Challenges for Heterodyne Instruments

Currently, at frequencies up to 2 THz, where solid-state local oscillators with enough available pump power [9] are available, heterodyne detectors are favored for high resolution spectroscopy. The reason being, heterodyne receivers at submillimeter wavelengths are within a factor of 2 to 10 of the quantum noise limit, the instrument backend can provide thousands of simultaneous channels with a wide range of spectral resolutions, and the direct detectors have a long way to go to achieve background limited sensitivity limits for high resolution ($R \approx 10^6$) spectroscopy. However, one of the major

challenges for the heterodyne receivers is the non availability tunable solid-state local oscillator sources for frequencies beyond 2 THz. Moreover, future space instruments will require heterodyne receivers with broad frequency coverage, with mixers ideally able to detect frequencies over several octaves [10]. Therefore, the mixer and receiver designs are needed to be improved substantially to have quantum limited performance over a very broad bandwidth.

Development of large arrays of heterodyne detectors at submillimeter wavelengths will be essential for future ground-based and space-borne observatories [11]. Only a handful of heterodyne array instruments with limited number of pixels are currently operational or being developed. Obviously, there are many challenges in developing large heterodyne arrays, such as the array architecture, mixer configuration, local oscillator power coupling, IF layout, and backend processing. Available LO power from solid-state sources is a major concern, and will be detrimental for the ultimate pixel count for such arrays.

Heterodyne instruments will also require to use novel receiver architectures to improve sensitivity and enable multi-pixel receiver integration. One such concept known as the ultimate receiver at submillimeter wavelengths is shown in Fig. 1, and is being developed at JPL/Caltech. A broadband dual-polarized receiver with image rejection mixers in a balanced configuration will be the ultimate receiver in this frequency range. Dual-polarized receivers detect both polarizations of an incoming radiation, thereby improving signal noise by $\sqrt{2}$ or reducing observing time by 2. Sideband-separating receivers reject noise from the image band and eliminate calibration uncertainty from sideband imbalance. Balanced mixers reject LO thermal noise and simplify LO injection eliminating the need for diplexers. All these make the ultimate receiver very attractive for heterodyne instruments, and such receivers are being developed at JPL at 1.5 THz for heterodyne array applications. It has been envisioned to develop the receiver components using silicon micromachining techniques, enabling integration of many components on a single wafer.

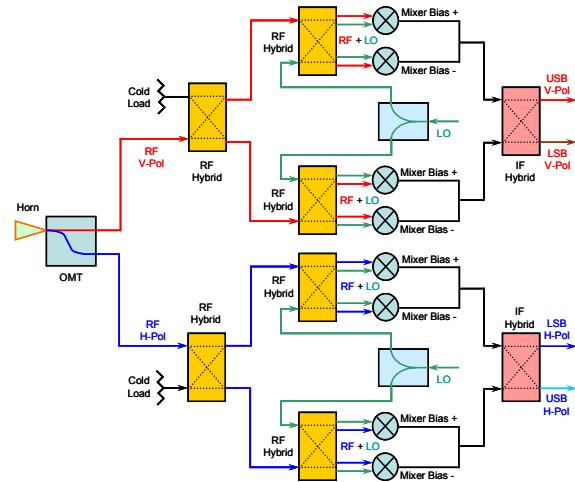


Fig. 1: Schematic diagram of the ultimate coherent receiver. The signal from the horn is split into two polarizations by the finline OMT. Each polarization uses three quadrature hybrids and an in-phase LO power splitter which couples to two sets of mixers with proper bias as shown. The two sets of IF for each polarization are combined in IF quadrature hybrids to provide the upper and lower sideband signal.

Conclusions

It is indeed true that direct detector instruments with cold telescopes will outperform heterodyne detectors eventually; there is a strong case for heterodyne receivers for high resolution spectroscopy studies. Heterodyne instruments will still provide substantial advantages in performance in many applications. However, progress in several fronts will be required to compete with direct detector instruments. Multi-pixel arrays with innovative receiver architectures such as the ultimate receiver and quantum limited sensitivity will give the heterodyne instruments an edge.

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